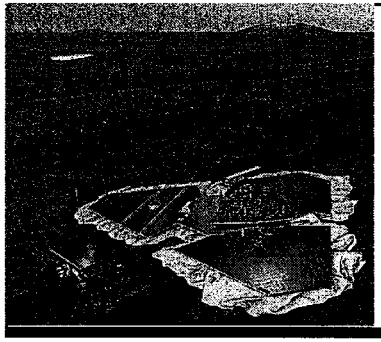
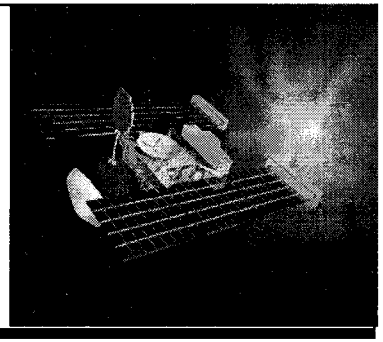


Probabilistic Risk Assessment for F-B-C NASA Space Missions



Dr. Ralph F. Miles, Jr.

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EER Systems Corporation
Montrose, California

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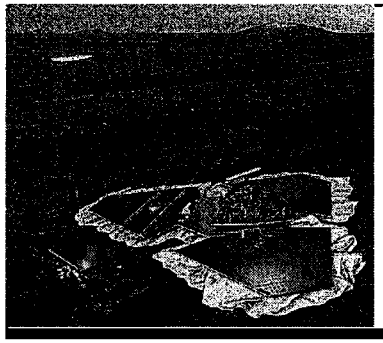
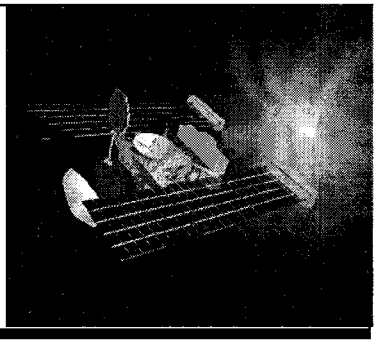
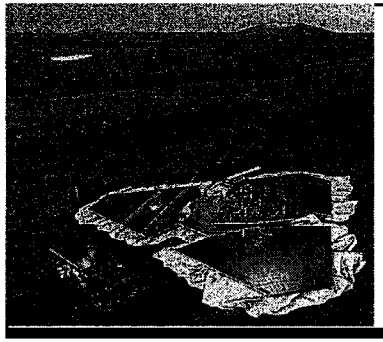


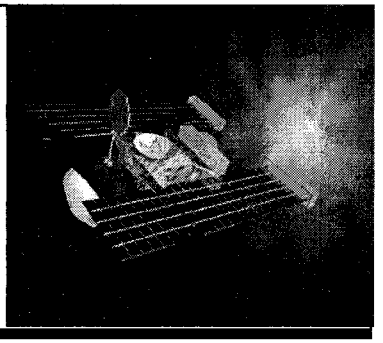
New NASA Strategic Environment



- **F-B-C: Faster, Better, Cheaper.**
  - No more "Flagship" projects.
  - Many launches a year.
  - Implementation time: 18 months.
- **LCA: Life-Cycle Cost Analysis.**
  - Cost before commitment.
  - Proposal development: One week.
- **ISE: Intelligent Synthesis Environment.**
  - Model-based design.
  - Petaflop (10^{15}) computing capability.

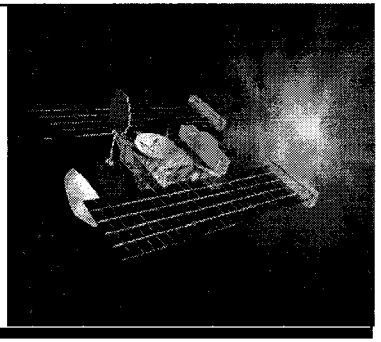


Intelligent Synthesis Environment



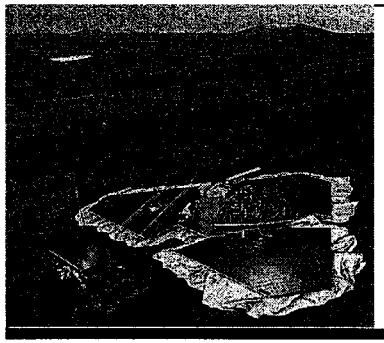
- **Need end-to-end product life-cycle simulation.**
  - **Reduce uncertainty.**
  - **Use geographically distributed talent.**
  - **Capture design knowledge early in life-cycle.**
  - **Convert data into knowledge.**
- **Fact: Large percentage of cost committed with only small percentage of knowledge.**
- **Problem: How to close gap between design knowledge and cost commitment.**

ISE Major Components

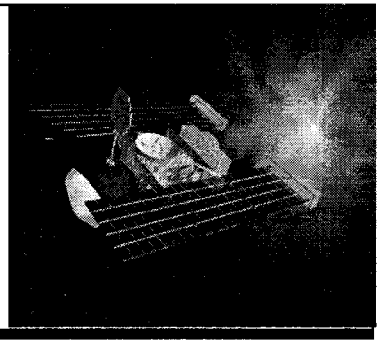


- **Components.**
  1. **Dynamical interaction between humans and computers.**
     - » CAVE, Vision, Dome.
     - » Entertainment industry far in lead.
     - » Rapid transition from data to intelligence.
  2. **Infrastructure for distributed collaboration between diverse teams across world.**
  3. **Tools for rapid synthesis and simulation tools.**
  4. **Tools to link complete life-cycle simulation in a virtual collaborative environment.**
- **Hardware requirements.**
  - **Petaflop (10^{15}) computing.**
  - **High-Speed Information Corridors.**
- **Cultural barrier.**

Ref: Dan Goldin, "Tools of the Future," NASA, Washington, DC, 31 January 1998.

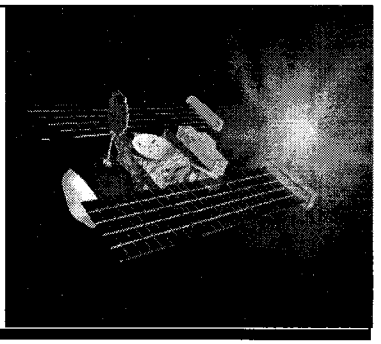


F-B-C Design Requirements

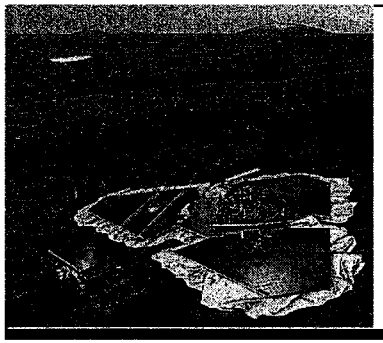


- **Model-Based designs.**
  - **Experts provide models which are compounded up to mission level.**
    - » **Design and analysis done in real-time.**
  - **Requires explicit incorporation of uncertainty.**
- **F-B-C does not permit "Worst-case designs."**
  - **Risk cannot be designed out of missions.**
- **Rapid development cycle.**
  - **Requires extensive expert judgment.**
    - » **Minimize analysis, test time and cost.**
- **Will require extensive probability elicitation.**
  - **For all uncertainties.**
    - » **Randomness of nature (Aleatory or IAEA Type A).**
    - » **Specification error (Model uncertainty or IAEA Type B).**
    - » **Completeness (Unknown unknowns).**

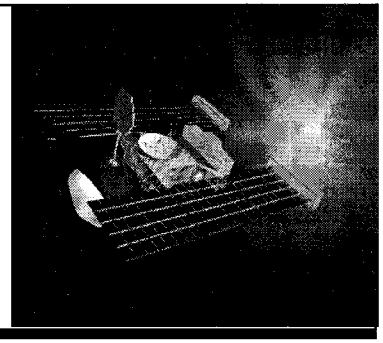
JPL Experience in Probabilistic Risk Assessment



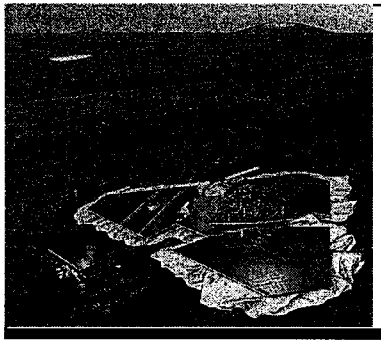
- **Flagship projects with Environmental Impact Statements.**
  - **Galileo to Jupiter (1989).**
  - **Ulysses to Jupiter and over the sun (1991).**
  - **Cassini to Saturn (1997).**
    - » **Launch: October 1997.**
    - » **Earth flyby: August 1999.**
    - » **Saturn arrival: 2005.**
- **Faster-Better-Cheaper Projects.**
  - **Mars Pathfinder (July 4, 1997 landing).**
  - **Stardust Project.**
    - » **Launch: 1999.**
    - » **Comet Wild 2: 2004.**
    - » **Earth return: 2006.**



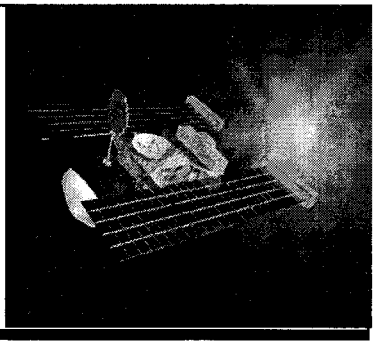
The Challenge



- **Elicit probabilities from engineers with severely constrained time limits.**
- **Elicit probabilities from engineers with no training in assessing uncertainty with subjective probabilities.**
- **Elicit probabilities with limited management support.**

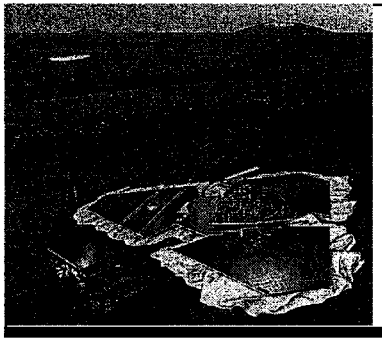


Two F-B-C Missions

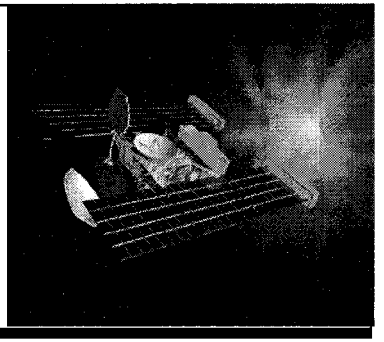


- **Mars Pathfinder.**
  - **Landed "Sojourner Truth" Rover on Mars July 4, 1997.**
  - **Risk assessment done to assess feasibility of design.**
    - » **Entry, descent, and landing of Lander.**

- **Stardust Project.**
  - **Launch in 1999.**
  - **Encounter Comet Wild-2 in 2004.**
  - **Flyby of Earth in 2006.**
  - **Release science capsule to land in Utah desert.**
  - **Risk assessment done to assess feasibility of design.**

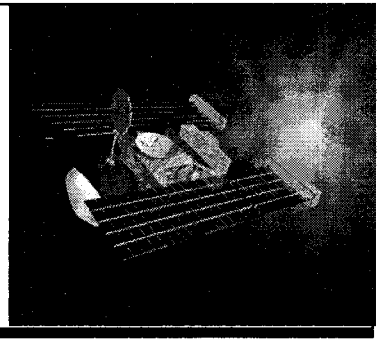


JPL Implementation of SRI Phases of Elicitation

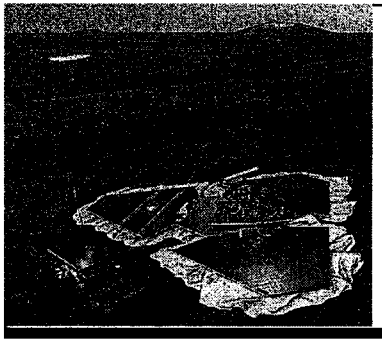


- **Motivating.**
  - Purpose.
  - Training.
- **Structuring.**
  - Done by System Engineer.
- **Conditioning.**
  - Discussion.
  - Training.
- **Encoding.**
  - Odds and reference events for extremes, equally likely for median.
- **Verifying.**
  - Examine and discuss resulting CDF.

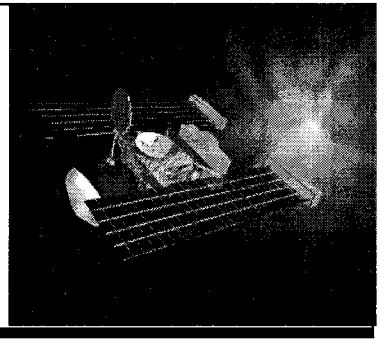
Quality of the Probabilistic Risk Assessment



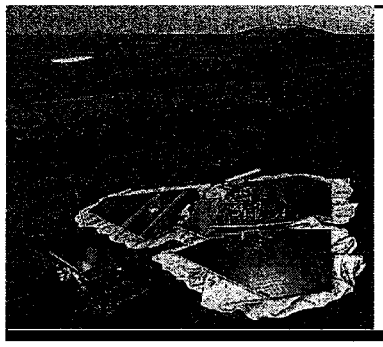
- **Requisite Model.**
  - **Everything in the model needed for decisions.**
  - **Nothing in the model not needed for decisions.**
- **Substantive Goodness in elicitation.**
  - **Provided by the technology expert.**
    - » **Innate talent.**
    - » **Education and engineering experience.**
    - » **Specific knowledge of the event.**
- **Normative Goodness in elicitation.**
  - **Provided by the elicitor.**
  - **Training for the technology expert.**



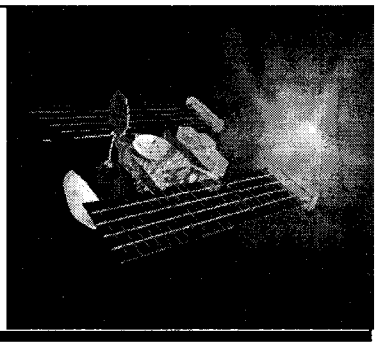
Requisite Models



- **Three step process.**
  1. **Project system engineer and risk assessor jointly developed Fault-Tree Model.**
  2. **Probability elicitation done with engineers cognizant for each critical event.**
  3. **Results "rationalized" by project engineer.**
- **Final result was expert opinion of project engineer.**
- **Fault-Tree was modeled in MS Excel.**
- **Uncertainties in failure of critical events.**
  - **Modeled as lognormal distributions.**
  - **CDF's of probabilities of failure.**
- **Monte-Carlo simulation for mission CDF.**

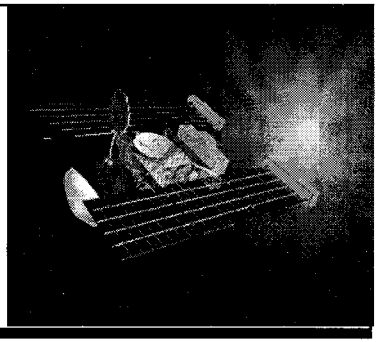


Training Session.



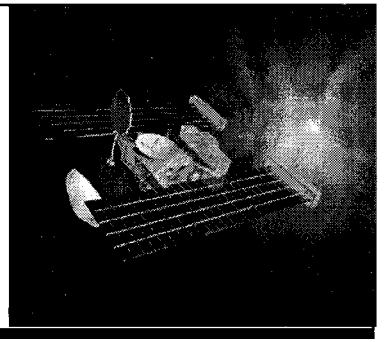
- **Not used for Mars Pathfinder EDL.**
  - **Problems resulted in confusing process with elicitation.**
- **Subsequently developed for Stardust Mission.**
- **Used Closing Dow Industrial 30 for same day.**
  - **Forty-five minute training session.**
- **Knowledge base.**
  - **Knowledge of market.**
  - **90 days previous data.**
- **Training session well received.**

Dow 30 Industrials Stock Index



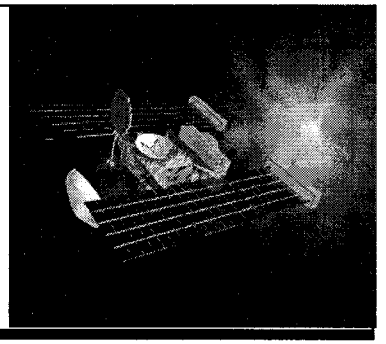
- Consider the Dow 30 Industrials Stock Index as an example of probability assessment.
- Given the data you are presented with and your prior knowledge, assess where the Dow will be at the end of the day.
- What are factors that could cause the Dow to be very low?
- What are factors that could cause the Dow to be very high?

1% Assessment of Dow

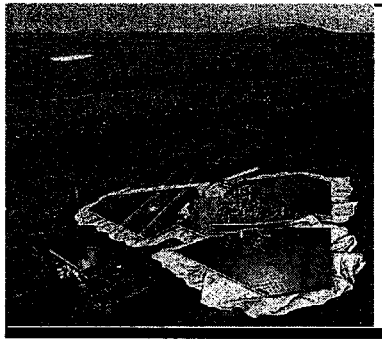


- This is called a "Bear Market."
- This is your most pessimistic assessment. It would be the value of the Dow if nearly all of the uncertainties were resolved unfavorably.
- This 1% assessment corresponds to Dow values for which the end-of-day values would be lower than your prediction only twice a year.
- For what value do you believe the Dow has only one chance in 100 of being lower at the end of the day?
  - Probability (1%) =

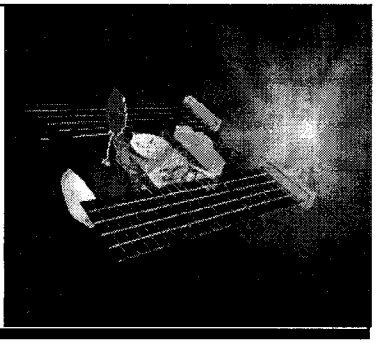
Assessment of Dow Probabilities



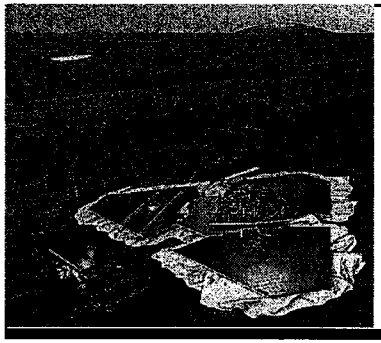
- For what probability do you believe the Dow has only x% chance of being lower at the end of the day?
  - Probability (1%) =
  - Probability (10%) =
  - Probability (50%) =
  - Probability (90%) =
  - Probability (99%) =



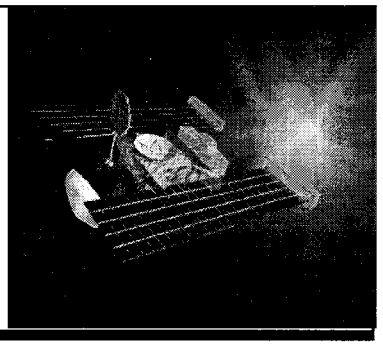
Sources of Knowledge for F-B-C Missions



- Taxonomy for sources of F-B-C NASA space knowledge.
  - Flight experience.
  - Testing.
  - Analysis.
  - Expert judgment.
- All knowledge is a combination of these sources.
- Expert judgment always present.

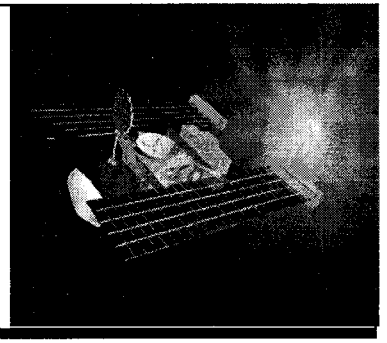


Thinking About Failures

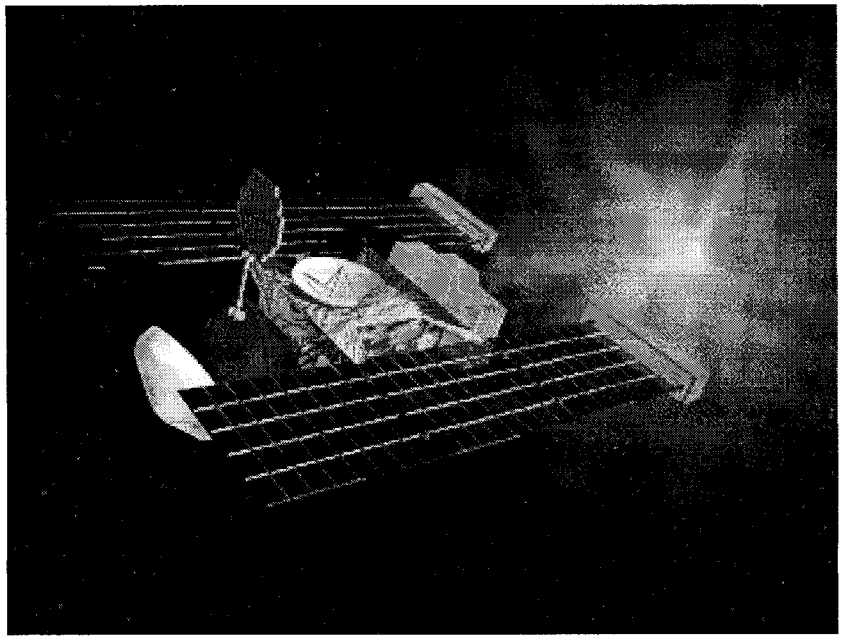


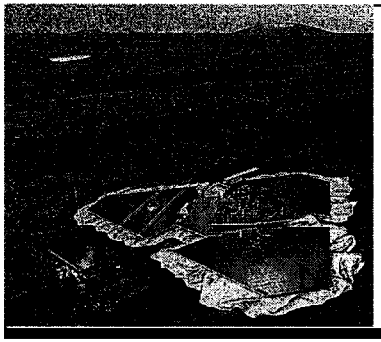
- **Three perspectives on failure probabilities.**
  1. **Think about design, implementation, and operations of similar complexity. How often would this result in failure?**
  2. **Repeat the design, implementation, and operation for your event many times. How often would this result in failure?**
  3. **Think of failure events in your life for which statistical evidence exists. Is the failure of your event more or less probable?**

Typical Elicitation VG

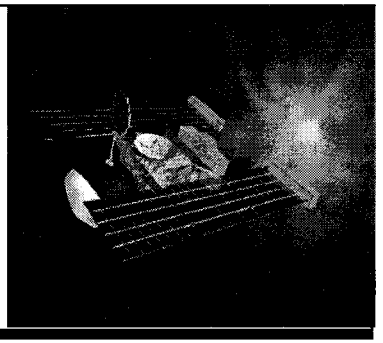


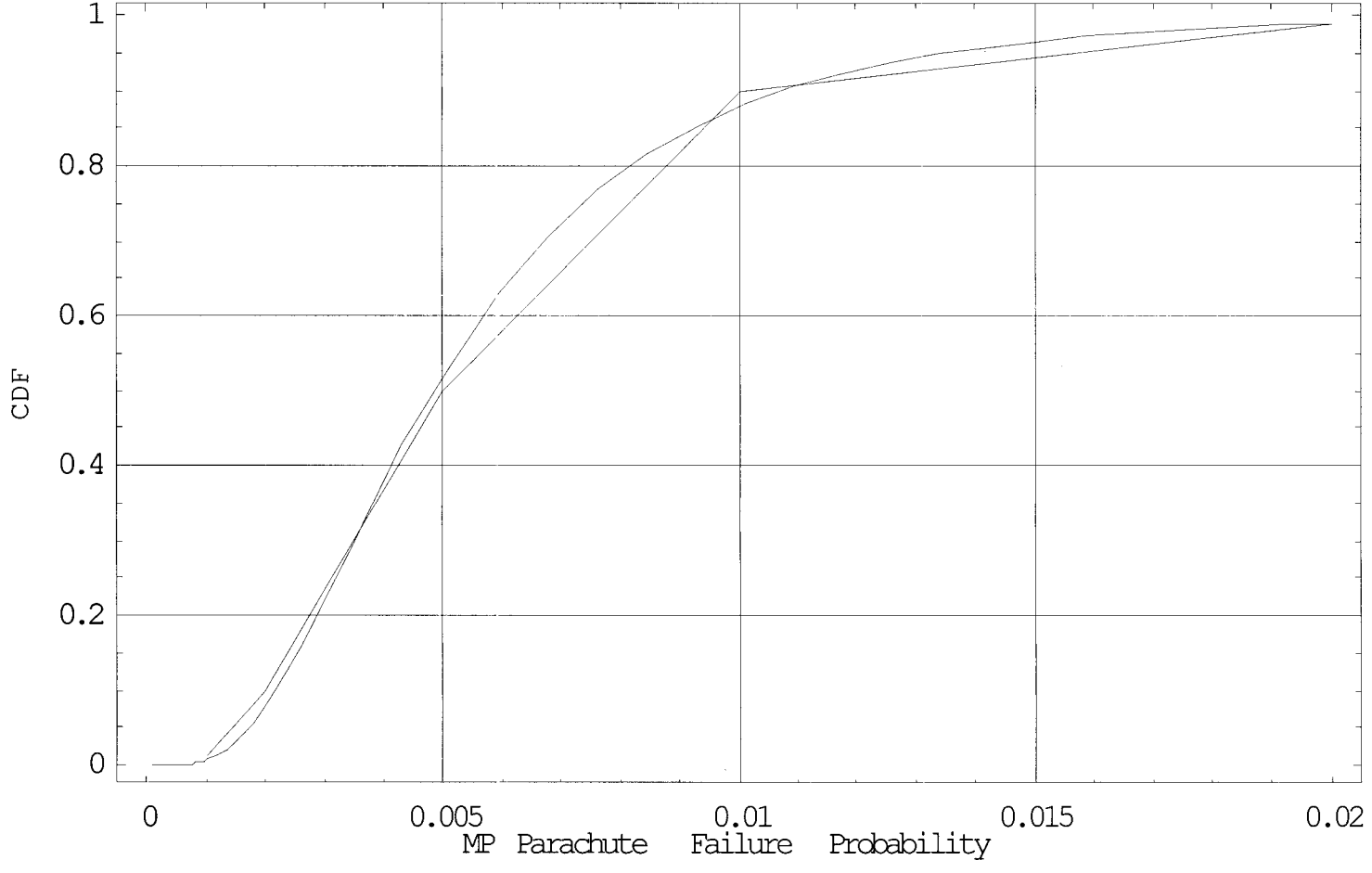
- This is your most optimistic assessment. It would be the failure probability if nearly all of the uncertainties were resolved favorably.
- For what probability do you believe the "true value," if it could be known, has only one chance in 100 of being lower?
  - Probability (1%) =

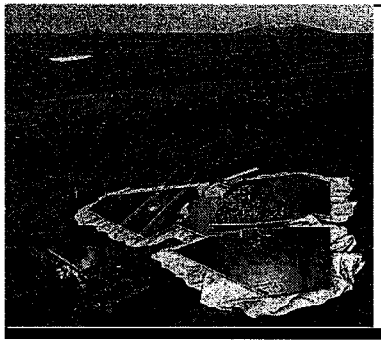




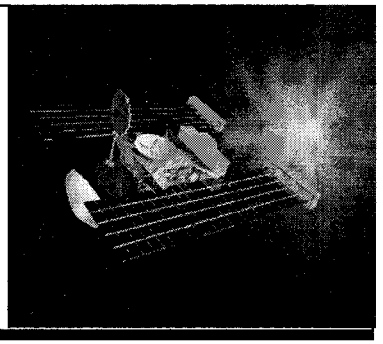
CDF Plot for Critical Event

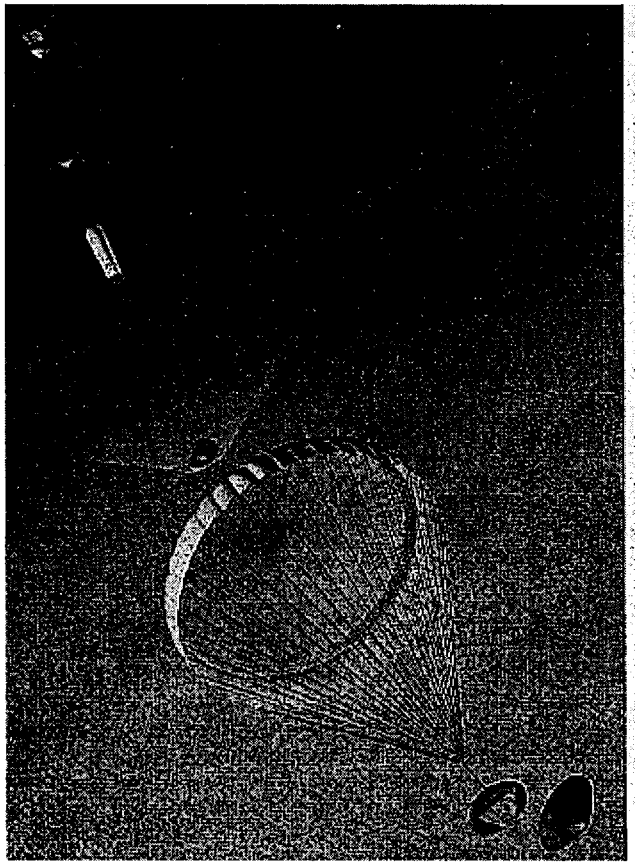


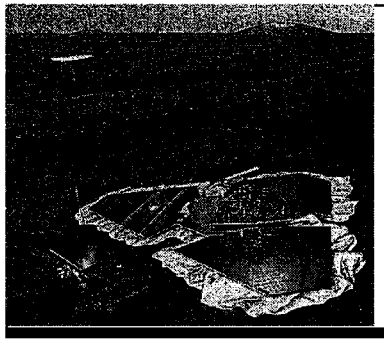




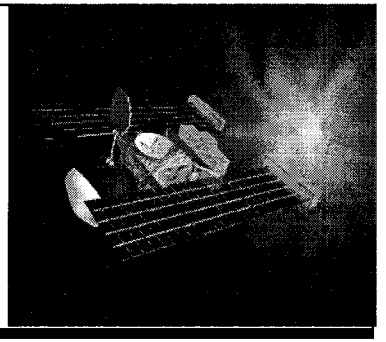
Mars Pathfinder Lander and Rover



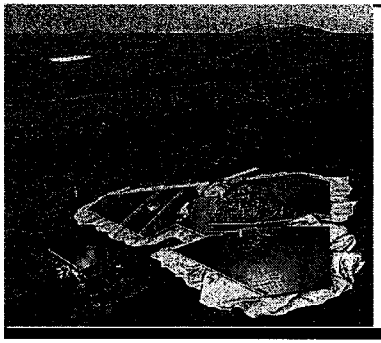




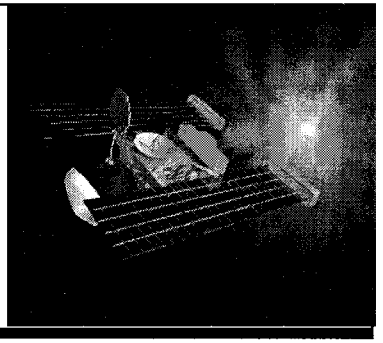
Mars Pathfinder Entry, Descent and Landing



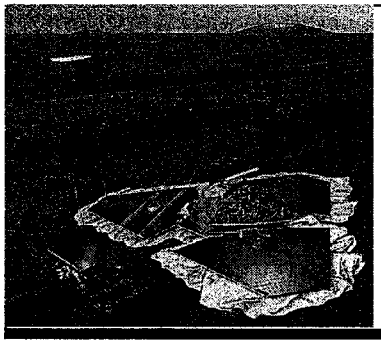
- ❑ Seven month cruise from Earth to Mars.
- ❑ Separate Lander from Cruise Stage (T - 35 min).
- ❑ Atmospheric entry with ablative heat-shield (T - 5 min).
- ❑ Parachute deploy and heat-shield separation (T - 2 min).
- ❑ Radar locks on Mars Surface (T - 25 sec).
- ❑ Airbags deploy (T - 5 sec).
- ❑ Retro-rockets fire (T - 3 sec).
- ❑ Free-fall from 15 meters (T - 1 sec).
- ❑ Bounce on surface and roll to stop (1 km).
- ❑ Deflate airbags and petal deployment (T + 3 hours).



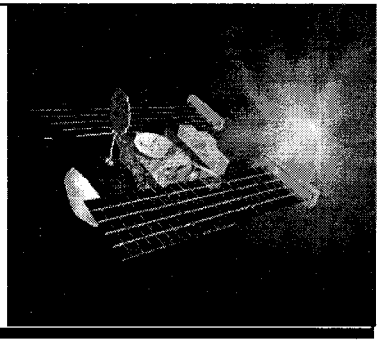
Mars Pathfinder Risk Assessment



- Entry-Descent-Landing risk assessment.
- All events in series--no redundancy.
- Mission modeled as series elements in MS Excel.
- Monte-Carlo simulation in @RISK.
- Cognizant engineers for each failure event interviewed.
- No training session for probability elicitation.
- Two Deputy Project Engineers independently assessed probability of failure at mission level.
- Results presented at launch-readiness review.
- PRA done too late in development to influence design.
- Did alert Project to areas needing extensive testing.



Mars Pathfinder Fault Tree

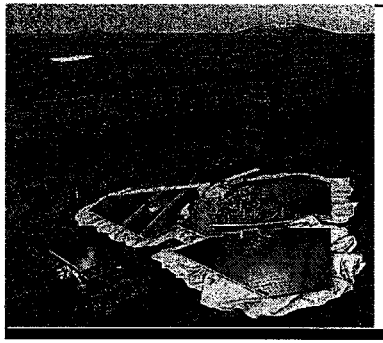


R. Miles September 12, 1996 Run SWT960812a. Data Set: S. Thurman 8/12/96

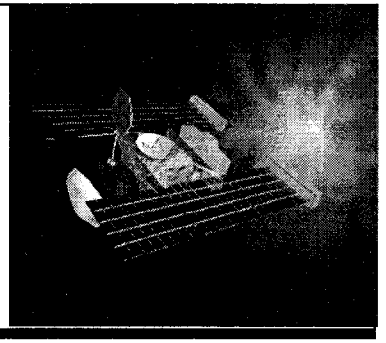
Latin-Hypercube Simulation; 10,000 trials.

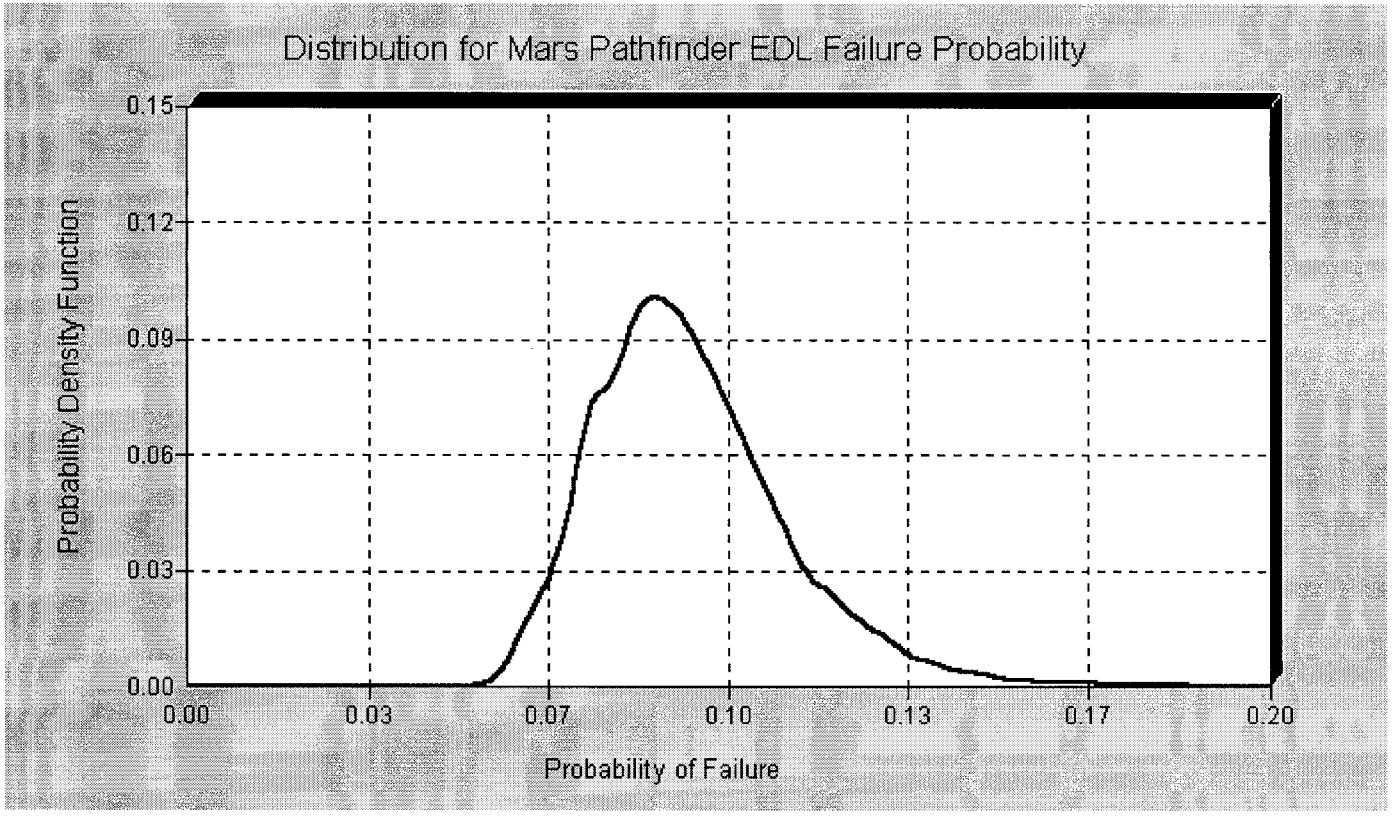
Mars Pathfinder EDL Failure Probability: 9.31%

Event			Probability		LogNorm Parm		LogNorm Dist		
			Median	90%	m	s	Mode	Mean	Std.Dev.
Entry, Descent, and Landing Failure								**9.3E-2**	**2.1E-2**
	1 Entry							**1.33E-2**	**4.8E-3**
		1.1 Cruise stage sep.	5.0E-4	1.0E-3	-7.60E+0	5.41E-1	3.73E-4	5.79E-4	3.37E-4
		1.2 Guidance error.	1.0E-3	2.0E-3	-6.91E+0	5.41E-1	7.46E-4	1.16E-3	6.75E-4
		1.3 Thermal protection.	5.0E-3	1.0E-2	-5.30E+0	5.41E-1	3.73E-3	5.79E-3	3.37E-3
		1.4 Parachute deploy.	5.0E-3	1.0E-2	-5.30E+0	5.41E-1	3.73E-3	5.79E-3	3.37E-3
	2 Descent							**4.93E-2**	**1.85E-2**
		2.1 Heatshield separate.	1.0E-3	2.0E-3	-6.91E+0	5.41E-1	7.46E-4	1.16E-3	6.75E-4
		2.2 Bridle deploy.	5.0E-3	1.0E-2	-5.30E+0	5.41E-1	3.73E-3	5.79E-3	3.37E-3
		2.3 Altimeter operate.	5.0E-3	1.0E-2	-5.30E+0	5.41E-1	3.73E-3	5.79E-3	3.37E-3
		2.4 Airbag inflation.	1.0E-2	3.0E-2	-4.61E+0	8.57E-1	4.80E-3	1.44E-2	1.50E-2
		2.5 Retro-rocket burn.	1.0E-2	2.0E-2	-4.61E+0	5.41E-1	7.46E-3	1.16E-2	6.75E-3
		2.6 Bridle cut.	1.0E-2	2.0E-2	-4.61E+0	5.41E-1	7.46E-3	1.16E-2	6.75E-3
	3 Landing							**2.76E-2**	**8.28E-3**
		3.1 Surface impact.	1.0E-2	2.0E-2	-4.61E+0	5.41E-1	7.46E-3	1.16E-2	6.75E-3
		3.2 Airbag retraction.	5.0E-3	1.0E-2	-5.30E+0	5.41E-1	3.73E-3	5.79E-3	3.37E-3
		3.3 Petal deploy.	1.0E-2	1.5E-2	-4.61E+0	3.16E-1	9.05E-3	1.05E-2	3.41E-3
	4	AIM Flight Computer	5.0E-3	1.0E-2	-5.30E+0	5.41E-1	3.73E-3	**5.79E-3**	**3.37E-3**

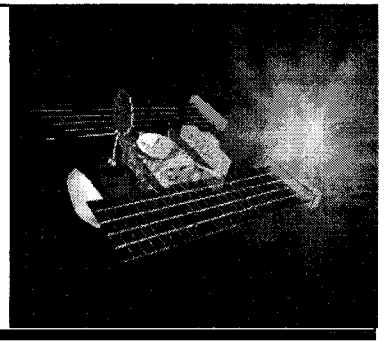


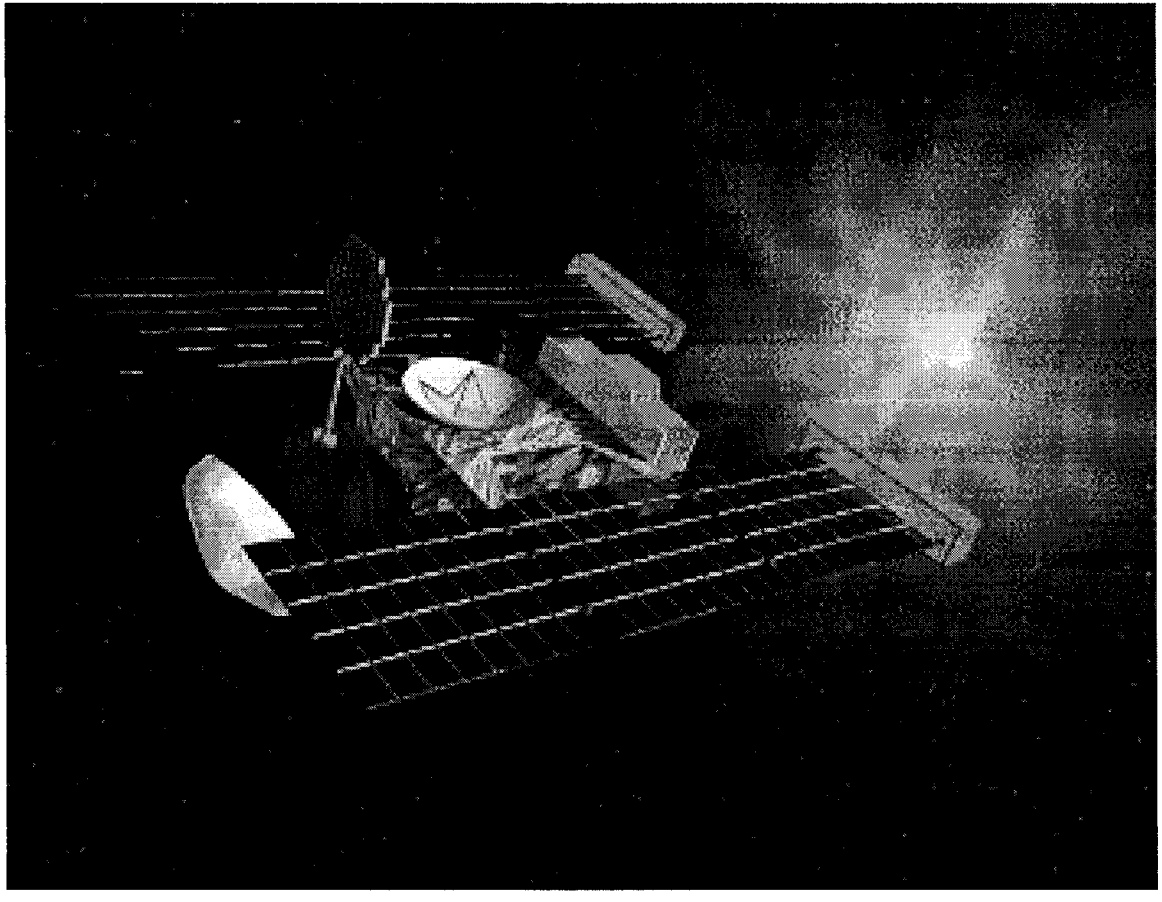
Mars Pathfinder PDF

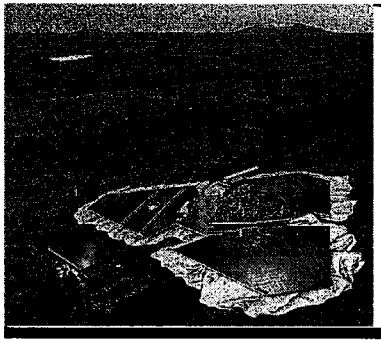




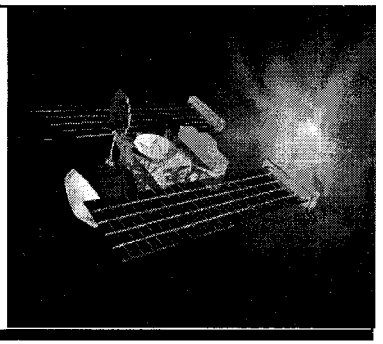
Stardust Spacecraft





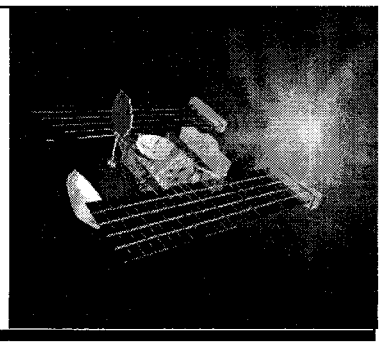


Stardust Risk Assessment

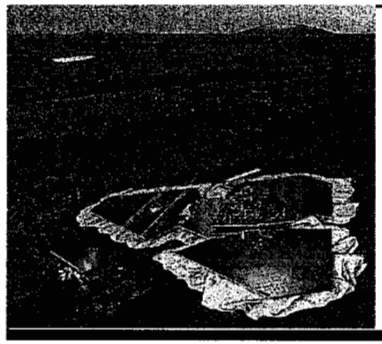


- Assessment from Launch Vehicle Separation to recovery of Science Capsule in Utah desert.
- All events in series---no redundancy modeled.
- Mission Modeled as series elements in MS Excel.
- Monte-Carlo simulation in JPL Excel Add-In.
- Training sessions for all probability assessors.
- Probabilities elicited from cognizant engineers.
- Project engineer reassessed probability of failure at mission level.
- Results not formally presented by Project.
- PRA done too late in development to influence design.
- Design conservatism obscured true risk.

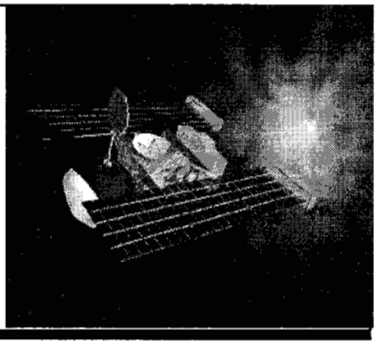
Prototype Stardust Fault Tree

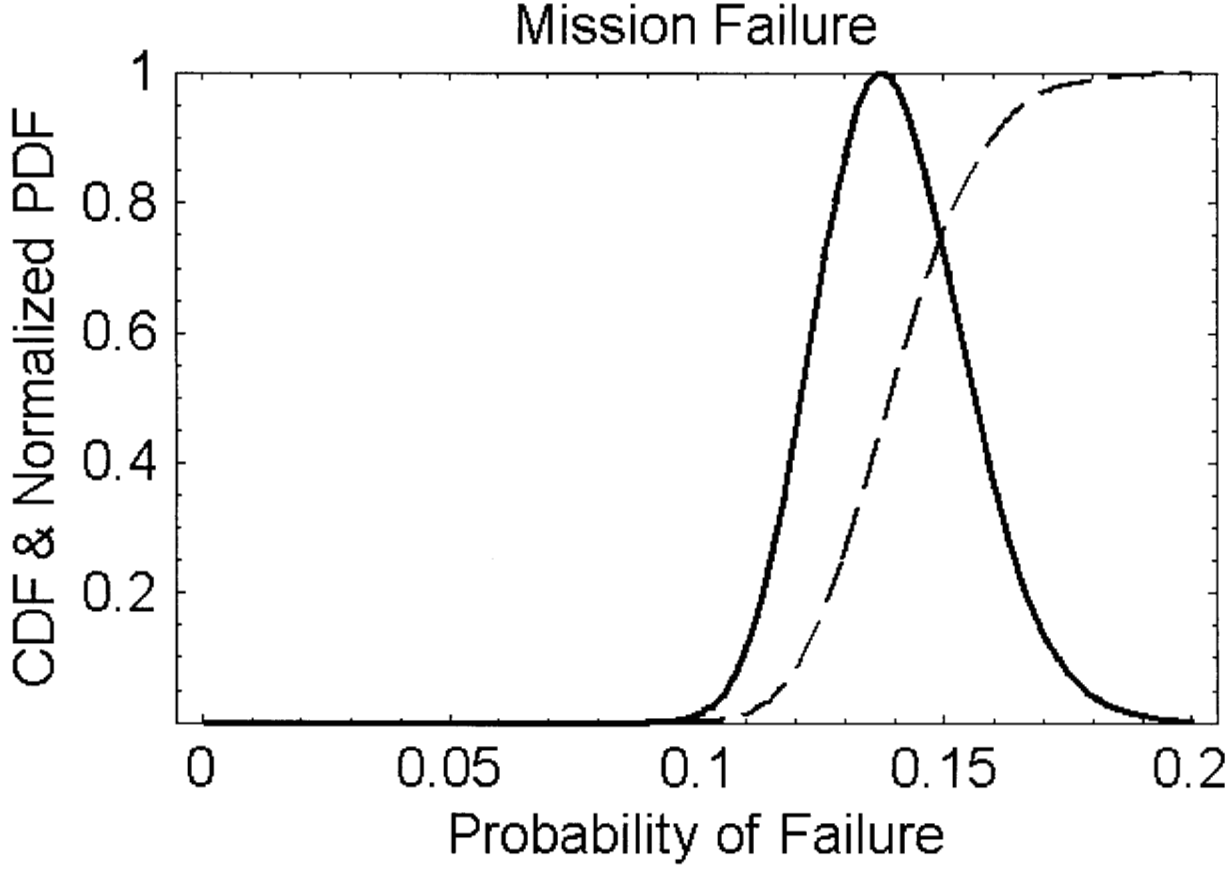


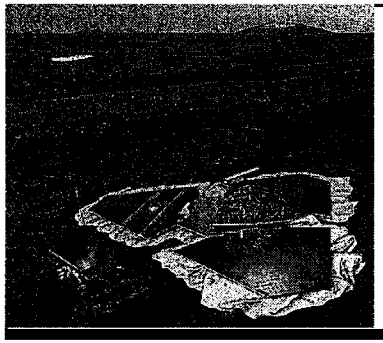
Event	Probability Distribution					Monte Carlo
	50%	90%	Type	Mean	StdDev	Mean
General						**2.295E-02**
S/C Structure (w/W hipple shield)	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
Aerogel performance	Not Credible Failure			0.000E+00	0.000E+00	0.000E+00
Propulsion (despin, TCM, jets)	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
Fuel Loading for entire mission	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
SRC Retention/Release	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
Launch						**1.154E-02**
Launch vehicle injection	Not considered			0.000E+00	0.000E+00	0.000E+00
Launch vehicle separation	Not considered			0.000E+00	0.000E+00	0.000E+00
ACS Despin	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
Solar Array Retention/Deployment	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
Cruise						**5.640E-02**
SRC deployment & retraction	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
Battery Operation	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
Star Cameras	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
Telecom Performance	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
Thermal performance	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
IMU & Accelerometer	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
ACS S/W in C&DH	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
C&DH Hardware	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
C&DH Software	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
Power	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
Comet Encounter						**1.154E-02**
C&DH - no reset or swap	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
ACS performance with impacts	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
Flyby trajectory	Not credible failure			0.000E+00	0.000E+00	0.000E+00
Collect 1,000 particles	Not credible failure			0.000E+00	0.000E+00	0.000E+00
Earth Return Phase						**4.538E-02**
SRC Structure	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
Aeroshell aerodynamics	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
SRC Avionics (w/o battery)	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
SRC Battery	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
Parachute	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
UHF Beacon	Not Credible Faliure			0.000E+00	0.000E+00	0.000E+00
Heatshield/TPS performance	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
SRC Vent	Not Credible Faliure			5.788E-03	3.374E-03	0.000E+00
Aerogel Canister Filter	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
Entry Trajectory	5.00E-03	1.00E-02	TLognormal	5.788E-03	3.374E-03	5.788E-03
Stardust Failure Probability:						**1.401E-01**



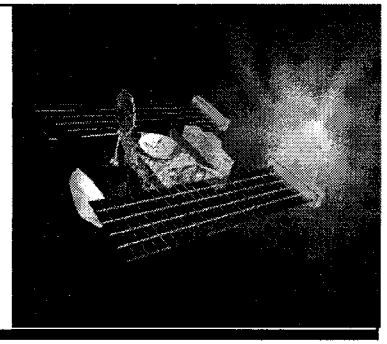
Prototype Stardust Mission PDF





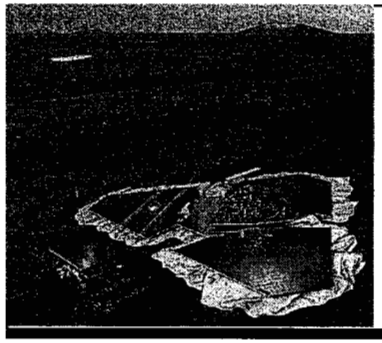


MBA* Criteria

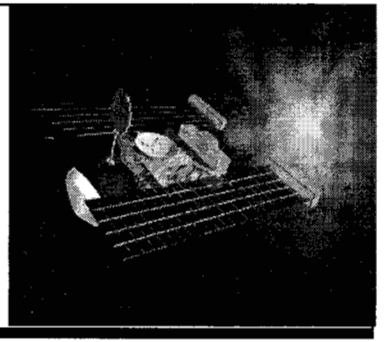


1. **Experts are poor processors of information.**
2. **Effective techniques for reducing overconfidence.**
3. **Decompose the problem.**
4. **Aggregate multiple experts.**
5. **Use structured group processes.**
6. **Combine expert judgments using math methods.**

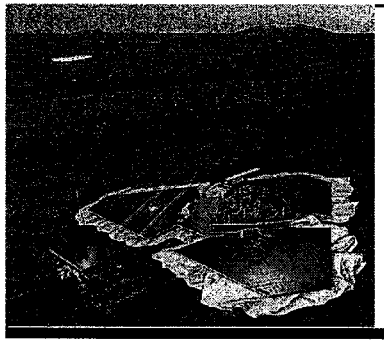
* A. Mosleh, V. M. Bier, and G. Apostolakis, *Methods for the Elicitation and Use of Expert Opinion in Risk Assessment: Phase 1 -- A Critical Evaluation and Directions for Future Research,* NUREG/CR-4962 and PLG-0533, Pickard, Lowe and Garrick, Inc., Prepared for the U.S. Nuclear Regulatory Commission, August 1987.



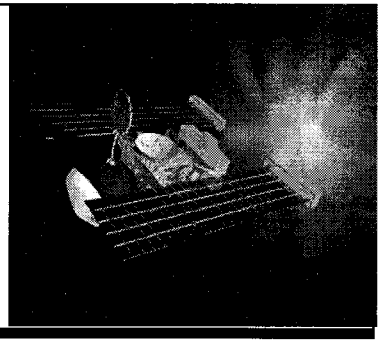
Critique of Process



- Done too late to influence design.
- Management and engineering biases present.
- Engineers don't understand statistical processes.
- Reluctance to accept subjective probabilities.
- Reluctance to accept PRA in general.

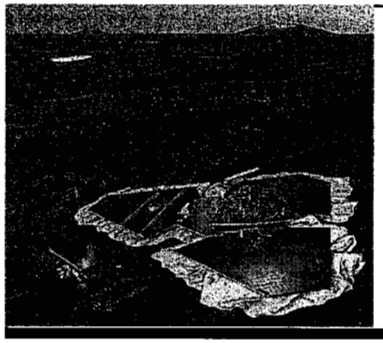


For Future Research

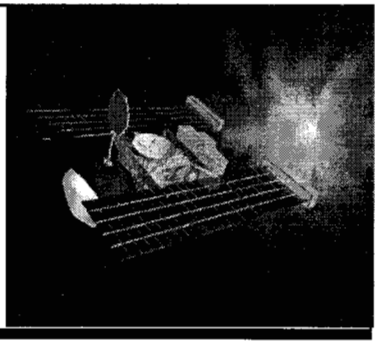


- ❑ **New methodology and new culture needed for control of biases.**
- ❑ **Is a probability of a probability a probability? ***
- ❑ **Display PDF to expert.**
  - **CDF yields little feedback.**
  - **Fitting standard PDF to elicited CDF yields some feedback.**
  - **Need differentiable CDF.**
    - » **With strong monotonicity for unimodal PDF.**
- ❑ **Relation between knowledge and PDF.**
  - **Perhaps information theory has something to contribute.**

* Brian Skyrms, "Higher Order Degrees of Belief," in *Prospects for Pragmatism, Essays In Honor of F. P. Ramsey,* D. H. Mellor (Ed.), Cambridge University Press, Cambridge, pp. 109-137, 1980.



Probability Elicitation References



- **MBA: Mosleh, Bier, and Apostolakis.**
  - **"Methods for the Elicitation and Use . . . In Risk Assessment"**
    - » **NUREG/CR-4962 & PLG-0533, August 1987.**
- **Hoffman, Hora, et al.**
  - **"A Guide for Uncertainty Analysis . . ."**
    - » **NCRP Comm. #14, 10 May 1996.**
- **Stanford/SRI/SDG/Stael von Holstein.**
- **Literature.**
  - **Von Winterfeldt and Edwards.**
  - **Morgan and Henrion.**
  - **Risk Analysis, Management Science, Plenum Press, JASA, Psychology, Nuclear Engineering, NRC, IEEE.**